Arnold Schwarzenegger
Governor

AN INTEGRATED ANTI-FOULING TECHNOLOGY FOR ENERGY EFFICIENT CHILLERS

INDEPENDENT ASSESSMENT AND FINAL EISG REPORT

Prepared For:
California Energy Commission
Public Interest Energy Research Program

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ENERGY INNOVATIONS SMALL GRANT (EISG) PROGRAM

INDEPENDENT ASSESSMENT REPORT (IAR)

AN INTEGRATED ANTI-FOULING TECHNOLOGY FOR ENERGY EFFICIENT CHILLERS

EISG AWARDEE

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LEGAL NOTICE

PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million of which 5% is allocated to the Energy Innovation Small Grant (EISG) Program. The EISG Program is administered by the San Diego State University Foundation under contract to the California State University, which is under contract to the Commission.

The EISG Program conducts up to four solicitations a year and awards grants for promising proof-of-concept energy research.

PIER funding efforts are focused on the following seven RD&D program areas:

- Residential and Commercial Building End-Use Energy Efficiency
- Energy Innovations Small Grant Program
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally-Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies

The EISG Program Administrator is required by contract to generate and deliver to the Commission a Feasibility Analysis Report (FAR) on all completed grant projects. The purpose of the FAR is to provide a concise summary and independent assessment of the grant project using the Stages and Gates methodology in order to provide the Commission and the general public with information that would assist in making follow-on funding decisions (as presented in the Independent Assessment section).

The FAR is organized into the following sections:

- Executive Summary
- Stages and Gates Methodology
- Independent Assessment
- Appendices
    - Appendix A: Final Report (under separate cover)
    - Appendix B: Awardee Rebuttal to Independent Assessment (Awardee option)

For more information on the EISG Program or to download a copy of the FAR, please visit the EISG program page on the Commission's Web site at:
http://www.energy.ca.gov/research/innovations

or contact the EISG Program Administrator at (619) 594-1049 or email
eisgp@energy.state.ca.us.

For more information on the overall PIER Program, please visit the Commission's Web site at
http://www.energy.ca.gov/research/index.html.

An Integrated Anti-Fouling Technology for Energy Efficient Chillers

EISG Grant # 00-23

Awardee:	J&D Thermo-Fluid Technology, Inc.
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PI Contact Info:	Phone: (856) 424-5122
	Email: Young@vortexaircon.com

Grant Funding:	$74,953
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Introduction

Chillers are major energy-consuming devices in large commercial and institutional buildings in California. They provide chilled water in central-air-conditioning systems in schools, hospitals, public and commercial buildings, and in industrial process equipment. The electricity consumed by medium-to-large chillers (200–2,000 tons) ranges from 0.25 kW/ton to 0.57 kW/ton, at 40% and full load respectively. A 2,000-ton system, operating at full load on a hot afternoon, will consume over one megawatt-hour per hour. Fouling of condenser tubes decreases chiller efficiency dramatically. To limit fouling, water in the cooling tower is drained to carry away the concentrated mineral salts, and fresh water is introduced. Fouling still occurs and results in increased electricity consumption. This is particularly serious on hot afternoons in California, when air conditioning consumes 30% of all electricity.

If the method studied in this project can alleviate the problem of fouling of the condenser tubes, chillers will run more efficiently during the entire cooling season, resulting in substantial and continuous savings in electricity. Increasing the efficiency of cooling systems will reduce the peak demand for electricity during the hottest days of the year and save a substantial volume of water.

This project studied a unique, electromagnetic precipitation and filtration method to prevent or mitigate fouling in chiller condenser tubes. It is based on two technologies: solenoid-induced precipitation and side-stream filtration. Solenoid-induced precipitation utilizes a square-wave pulsating current to create time-varying magnetic fields. The magnetic fields then produce an induced, pulsating electric field in the circulating water. The electric field causes excess mineral ions such as calcium and magnesium in cooling-tower water to precipitate as mineral salts. These salts provide nucleation sites for other dissolved mineral ions. As the cooling-tower water continuously circulates, the precipitated seed crystals grow into larger particles that are removed by side-stream filtration. Removal of scale-causing mineral ions from cooling-tower water prevents or significantly mitigates fouling at the condenser tubes, resulting in direct electricity savings. The removal of mineral ions by the side-stream filtration system also permits an increase in the concentration cycle of the cooling water, resulting in substantial water savings[1].

[1] The concentration period is the time period between replacements of the cooling water.

Objectives

The goal of this project was to determine the feasibility of using solenoid-induced precipitation and side-stream filtration to maintain 90% heat-transfer efficiency of chiller condensers by limiting scale deposits on the condensers. The researchers established the following project objectives:

1. Fabricate a prototype system using both solenoid-induced precipitation and side-stream filtration for medium-to-large chiller applications (greater than 200 tons).
2. Demonstrate that this technology can limit scale deposits to maintain 90% heat-transfer efficiency using a concentration cycle of five.
3. Demonstrate that this technology can limit scale deposits to maintain 90% heat-transfer efficiency using a concentration cycle of eight.

Outcomes

1. The researcher constructed a test-flow loop that consisted of a laboratory cooling tower, heat-transfer test section, an automatic blow-down system, a flow meter, solenoid-induced precipitation, and side-stream filtration.
2. The researcher conducted fouling tests using a high heat flux of 90-100 kW/m^2 in order to accelerate the fouling process, a practice common among fouling researchers. Controls limited variation of the electric conductivity of circulating water in the simulated cooling tower to within 5% of the set conductivity value. A solenoid valve controlled the blow-down using input from the electric conductivity meter. This test ran for five cycles of concentration. The heat transfer coefficient remained above 90% for 150 hours with no detectable trend to lower values.
3. The test procedure used for eight cycles of concentration was similar to the above. In this test the heat-transfer coefficient remained above 90% for 150 hours, with no detectable trend to lower values. In a control test, the heat-transfer coefficient dropped below 90% after about 50 hours and displayed a marked downward linear trend thereafter.

Conclusions

1. This project successfully constructed an experimental apparatus to test the feasibility of the method.
2. The heat-transfer coefficient remained above 90% for 150 hours and five cycles of concentration.
3. The heat-transfer coefficient remained above 90% for 150 hours and eight cycles of concentration.
4. Particulate matter captured in the side-stream filter caked into a hard substance during the test. Continued operation would result in an inoperable filter. Some back-washable filters are designed specifically to reduce the accumulation of calcium carbonate scale crystals so that the scaling is minimized and does not become a problem. It is recommended that tests be done to verify the benefit of these filters when operating specifically in the conditions created by the use of this method.

Based on findings in this project, chiller condensers equipped with a device incorporating this method could be operated within 10% of maximum peak performance. This could result in significant energy savings for operators of medium-to-large chillers. The present project demonstrated the feasibility of integrated anti-fouling technology.

Recommendations

The manner in which particulates are filtered from water remains a technical challenge for this project that must be solved prior to commercialization. Calcium carbonate and other crystals accumulated at the top of the filter medium, caking into a hard substance over time. The researcher must redesign the filter to avoid caking of calcium carbonate scale crystals. Some filters are designed to be back-washed to reduce the accumulation of materials. Other solutions should also be investigated. Once that problem has been overcome, the researcher should work directly with a commercial chiller manufacturer. That work should entail integration into standard commercial products and a field test of prototype units.

After taking into consideration: (a) research findings in the grant project, (b) overall development status as determined by stages and gates, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for follow-on funding within the PIER program.
Receiving follow-on funding ultimately depends upon: (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. The heat-transfer performance of water-cooled chillers degrades as the condenser tubes become fouled with water contaminants. As fouling decreases the efficiency of the chiller, energy consumption increases. Typically, a large chiller runs at 0.6 kW/ton when its condenser tubes are clean and free of scale. When the condenser tubes become fouled, the chiller runs at a level greater than 0.8 kW/ton, a 33% increase in energy consumption. The IAF technology keeps the condenser tubes relatively free of fouling, thus maintaining the initial energy-consumption rate for large chillers. For a 100-ton chiller this technology could save about 480 kWh/day. At $0.06 per kWh, this is $28.80 per day or over $10,000 per year. The cost of the implementation of the technology is relatively small compared to the potential savings. The PA estimates the simple payback period would be less than one year

If the results from the project are widely used in California, water-cooled chillers can be operated near initial peak efficiency. Ratepayers who operate large chillers will be the primary beneficiaries. Other ratepayers will benefit from the decreased load on the grid during peak summer hours, when air conditioners are widely used.

Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researcher's overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

This researcher's company has a marketing strength because it is integrating filtration and an electronic descaling system into a single package. Most other manufacturers provide only filtration systems or electronic descaling systems. Only a few development-stage companies have begun selling these technologies together as a package, and there is little scientific data to support their marketing efforts. This project gives J&D much of the data the others lack to convince the marketplace of the viability of this technology. J&D is exploring strategic relationships with manufacturers of filtration systems that will combine their market expertise and existing distribution capabilities with J&D's research and technology innovations.

Engineering/Technical

J&D proved technical feasibility of the "integrated anti-fouling" (IAF) technology through laboratory-based testing. The researcher must still resolve problems associated with particulate clogging of the filter. Note, however, that the purpose of the filter is to collect the particulates, and a common technical solution is to replace clogged filters. Once the best-cost filter configuration has been identified, the technology should be developed into a product prototype and submitted to field-testing. J&D is exploring opportunities to install IAF technology in chillers located in Philadelphia-area universities for the 2003 cooling season. Manufacturers of filtration systems and other peripheral components have agreed to support this field-testing stage.

Legal/Contractual

J&D has entered into confidentiality agreements for research testing only. J&D has not formed any other binding legal or contractual agreements with potential strategic partners or made any commitments to distribution relationships with them. There is no evidence that J&D has applied for patent protection.

Environmental, Safety, Risk Assessments/ Quality Plans

Quality Plans include Reliability Analysis, Failure Mode Analysis, Manufacturability, Cost and Maintainability Analyses, Hazard Analysis, Coordinated Test Plan, and Product Safety and Environmental**.** Chiller applications face a broad range of bio-fouling issues, ranging from algae to Legionella, that present significant risk to the marketplace and to local communities. The researcher must implement specific product-safety and quality plans to handle this issue before this technology can be released to the market.

Production Readiness/Commercialization

J&D believes it can produce product prototypes of IAF technology for near-term field testing. The PA believes additional work must be completed in the areas of filter life, bio-fouling, and product safety before the technology should be applied. While the technology is not yet ready for mass production, the researcher is making appropriate contacts with companies who market related products.

Appendix A: Final Report (under separate cover)

Appendix B: Awardee Rebuttal to Independent Assessment (none submitted)

ENERGY INNOVATIONS SMALL GRANT (EISG) PROGRAM

EISG FINAL REPORT

AN INTEGRATED ANTI-FOULING TECHNOLOGY FOR ENERGY EFFICIENT CHILLERS

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Legal Notice

Inquires related to this final report should be directed to the Awardee (see contact information on cover page) or the EISG Program Administrator at (619) 594-1049 or email eisgp@energy.state.ca.us.

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Abstract

The objective of the project was to develop a technology to prevent or mitigate mineral fouling in the condenser tubes of large chillers. The technology which is referred as an integrated anti-fouling (IAF) technology uses both a solenoid-induced coil device and filtration. The core concept of the technology is that the coil device produces mineral particles in water, and the particles are removed by the filtration in the IAF technology, resulting in the prevention of mineral fouling. The project conducted a series of heat transfer fouling experiment, and the test results demonstrated the validity of the IAF technology, by achieving the objective of maintaining 90% of the peak heat transfer performance of a heat exchanger. Since many chillers lose top heat transfer performance over time due to the fouling, the IAF technology can provide the efficient operation of the chillers by preventing the fouling. Thus, the IAF technology can be used as an energy conservation measure as clean chillers do not consume the electricity as much as fouled chillers. The IAF technology is market ready now, and the next step is a field demonstration for an extensive pilot study. Since the IAF technology uses electromagnetic fields instead of scale-inhibiting chemicals, it is an environmentally friendly technology. Thus, it can significantly reduce chemicals that cause water pollution. Furthermore, the IAF technology saves water consumption as manifested by the test results in the project, where the IAF technology maintained heat transfer tubes scale free even at the cycle of concentration of 8.

Key Words: fouling, integrated anti-fouling, filtration, chiller, cooling tower, energy conservation, water conservation

Executive Summary

1. Introduction

This project belongs to the PIER Subject Area of Building End-Use Efficiency. Chiller is one of the major energy consuming equipment from the building end-use point of view. Chillers are used as central air conditioning systems in residential, school, hospital, public and commercial buildings and as process equipment to provide chilled water in many industries. The electricity consumed by medium to large size chillers (10 – 2,000 tons) is a major portion of total electric consumption in California and worldwide. These chillers are often water cooled, and fouling in chiller tubes (or more specifically condenser tubes) decreases chiller efficiency, thereby substantially increasing the consumption of electricity, particularly during the cooling season. A proposed integrated anti-fouling (IAF) technology can prevent or mitigate fouling in condenser tubes, and subsequently chillers can be made to run more efficiently during the entire cooling season. This will result in substantial and continuous savings in electricity. Another major benefit of the IAF technology is the substantial reduction of peak electricity demand levels generated by space cooling systems during the hottest days of the year.

The IAF technology uses solenoid-induced precipitation and side-stream filtration. Solenoid-induced precipitation utilizes a square-wave pulsing current to create time-varying magnetic fields, which in turn produce an induced pulsating electric field in the circulating water, known as Faraday's law. Excess mineral ions such as calcium and magnesium in cooling-tower water precipitate out as mineral salts, providing nucleation sites for other dissolved mineral ions. As the cooling-tower water is continuously circulated, the precipitated seed crystals grow into larger particles, which are then removed by side-stream filtration. When the scale-causing mineral ions are removed from the cooling-tower water, fouling at the condenser tubes can be prevented or significantly mitigated, resulting in direct electricity savings. Another significant benefit is water saving, a major issue in California and worldwide. As the side-stream filtration system removes mineral ions, the cycle of concentration in the cooling water can be increased, thus resulting in substantial water savings.

The project has fabricated the integrated anti-fouling test facility, conducted a series of tests, and successfully demonstrated that the heat exchanger could maintain 90% of the original efficiency with the IAF treatment. The concept has been proved at laboratory and ready to be implemented at the field. Full-scale pilot field test is planned with a local public facility. The detail test results will be given in Project Outcome section, including fouling resistance curves, heat transfer coefficient curves, photographs of fouled heat transfer tube surface, and scanning electron microscopy photographs of scale samples.

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2. Project Objectives

The Objectives of the project were to develop a prototype integrated anti-fouling (IAF) technology, which uses both a solenoid-induced precipitation and a side-stream filtration for medium to large chiller applications, to demonstrate that IAF technology can limit scale deposits to maintain 90% heat transfer efficiency using cycles of concentration of 5 and 8 for condenser tubes.

3. Project Outcomes

A prototype integrated anti-fouling (IAF) technology, which uses both a solenoid-induced precipitation and a side-stream filtration, was fabricated. The concept of the IAF technology was experimentally validated. The cycles of concentration used in the project were 5 and 8, which indicate higher cycles than the cycle used in a typical chiller. The performance of the IAF technology was evaluated by measuring the heat transfer coefficient in a heat exchanger. Inlet and outlet temperatures of the cold and hot water were measured, from which one calculated the universal heat transfer coefficient. The project demonstrated that the universal heat transfer coefficient could be maintained at 90% of initial peak values for the cycles of concentration of both 5 and 8. Fouling resistance curves over time were also obtained from the universal heat transfer coefficient curves, which clearly indicated the benefit of the IAF technology and the validity of the technology. Photographs of fouled heat transfer surfaces were taken, which demonstrated that the IAF technology could keep the heat transfer surface scale free.

4. Conclusions

The project has successfully developed and validated an Integrated Anti-Fouling (IAF) technology through experimental tests. The IAF technology consisted of electronic descaling system and filtration. The overall heat transfer coefficients in a heat transfer test section using a chiller tube were maintained 90% efficiency compared with those of the clean scale-free state for cycles of concentration of both 5 and 8.

Based on the findings in the project, the chillers if equipped with the IAF technology can be operated within 90% of the maximum peak performance, resulting in significant energy savings. The present project clearly demonstrated that the combined use of the electronic descaling system and filtration, which is referred as the IAF technology, is a technology that is ready for commercialization.

5. Recommendations

One of the technical challenges involved in the commercialization of the IAF technology is in the use of filter. The project found that the calcium carbonate scale crystals were accumulated at the top of filter medium, caking into a hard concrete with time. This requires a design change in the filter so that the caking of calcium

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carbonate scale crystals can be avoided. Some of the back-washable filters are designed specifically to reduce the accumulation of calcium carbonate scale crystals so that the problem can be minimal, thus not causing the caking problem. Thus, it is recommended that tests be done to verify the benefit of some of these new designs specifically from the point of preventing caking of calcium carbonate scale crystals.

6. Public Benefits to California

The heat transfer performance of a water-cooled chiller degrades as the condenser tubes become fouled as water is used as a heat transfer medium. As the fouling decreases the efficiency of the chiller, the energy consumption increases. Typically, a large chiller runs at 0.6 kW/ton when its condenser tubes are clean, scale free. When the condenser tubes become fouled, the chiller runs at a level substantially greater than 0.8 kW/ton. The result in the project provides a solution to maintain the condenser tubes clean, scale free, thus maintaining the initial energy consumption for large chillers. The cost of the implementation of the technology is relatively small compared to the increased energy cost due to fouling in the condenser tubes at large chillers. If the results from the project is widely used in water-cooled chillers in California, water-cooled chillers can be operated it their initial peak efficiency.

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Introduction

This project belongs to the PIER Subject Area of Building End-Use Efficiency. One of the major energy consuming equipment from the building end-use point of view is chiller.

Chillers are used as central air conditioning systems in residential, school, hospital, public and commercial buildings and as process equipment to provide chilled water in many industries. The electricity consumed by medium to large size chillers (10 – 2,000 tons) is a major portion of total electric consumption in California and worldwide. These chillers are often water cooled, and fouling in chiller tubes (or more specifically condenser tubes) decreases chiller efficiency, thereby substantially increasing the consumption of electricity, particularly during the cooling season. A proposed integrated anti-fouling (IAF) technology can prevent or mitigate fouling in condenser tubes, and subsequently chillers can be made to run more efficiently during the entire cooling season. This will result in substantial and continuous savings in electricity. Another major benefit of the IAF technology is the substantial reduction of peak electricity demand levels generated by space cooling systems during the hottest days of the year.

The IAF technology uses solenoid-induced precipitation and side-stream filtration (see Appendix I for more details). Solenoid-induced precipitation utilizes a square-wave pulsing current to create time-varying magnetic fields, which in turn produce an induced pulsating electric field in the circulating water. Excess mineral ions such as calcium and magnesium in cooling-tower water precipitate out as mineral salts, providing nucleation sites for other dissolved mineral ions. As the cooling-tower water is continuously circulated, the precipitated seed crystals grow into larger particles, which are then removed by side-stream filtration. When the scale-causing mineral ions are removed from the cooling-tower water, fouling at the condenser tubes can be prevented or significantly mitigated, resulting in direct electricity savings. Another significant benefit is water saving, a major issue in California and worldwide. As the side-stream filtration system removes mineral ions, the cycle of concentration in the cooling water can be increased, thus resulting in substantial water savings.

The project has fabricated the integrated anti-fouling test facility and conducted a series of tests to demonstrate that the heat exchanger can maintain 90% of the original efficiency with the IAF treatment. The concept has been proved at laboratory and ready to be implemented at the field. Full-scale pilot field test is planned with a local public facility. The detail test results will be given in Project Outcome section, including fouling resistance curves, heat transfer coefficient curves, photographs of fouled heat transfer tube surface, and scanning electron microscopy photographs of scale samples.

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Project Objectives

Objective 1: Fabricate a prototype integrated anti-fouling (IAF) technology, which uses both a solenoid-induced precipitation and a side-stream filtration for medium to large chiller applications.

Objective 2: Demonstrate that IAF technology can limit scale deposits to maintain 90% heat transfer efficiency using cycle of concentration of 5.

Objective 3: Demonstrate that IAF technology can limit scale deposits to maintain 90% heat transfer efficiency using cycle of concentration of 8.

Objective 4: Demonstrate that IAF technology can maintain a heat transfer coefficient of over 90% for the chiller tubes.

Project Approach

Task 1:
Sub-Task 1-1: Installation of solenoid-induced precipitation (SIP) device in bench-test setup.

The installation of SIP device was completed in the first month of the project.

Sub-Task 1-2: Installation of a side-stream filtration system in bench-test setup

The test setup has been completed with a solenoid-induced precipitation device and filtration system installed in the first month.

Task 2: Generate a test plan and deliver to EISG Program Administrator for review and approval.

A test plan was completed in the second month and submitted for review and approval. The test plan is attached as Appendix III at the end of this report.

Task 3: Obtain baseline fouling factor data and photographs with no treatment.

The concentration of water was controlled using an automatic discharge system, which operated based on the measurement of the electric conductivity of cooling tower water. We completed a baseline test for the case of COC of 5 and fouling resistance data.

Task 4: Obtain fouling data and photographs with IAF technology for cycle of 5.

The test with treated by IAF technology was completed with 10% side-stream filtration (using a 5-μm fabric filter). The case of IAF treatment showed practically no fouling on the heat exchanger as manifested by the values of the fouling resistance. The results clearly indicated that the IAF technology kept the heat exchanger scale free for the case of COC of 5. We repeated the test with a sand filter of 20-μm size.

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Task 5: Obtain fouling data and photographs with IAF technology for cycle of 8.

The tests were conducted with and without IAF treatment (without filtration). The data obtained without the treatment provide the baseline data. The fouling resistance obtained with IAF was significantly less than the case of the no treatment and showed an almost perfectly clean surface at the end of the test. On the other hand, the case with the no treatment showed a heat transfer surface completely covered by scale.

Task 6: Quantify reductions in fouling rate over the baseline

Based on the fouling resistance data over time, the percentage reduction due to the application of the IAF technology was found to be over 90%.

Task 7: Perform reporting requirements (Progress Reports and Final Report)

90 day progress reports were prepared and submitted. The final report has been prepared for review.

Project Outcomes

Presentation of Results

The first objective of the project was to fabricate a prototype integrated anti-fouling (IAF) technology, which uses both a solenoid-induced precipitation and a side-stream filtration for medium to large chiller applications.

We constructed a test flow loop as shown in Fig. 1, which consists of a laboratory cooling tower, heat transfer test section, an automatic blowdown system based on the readings from an electric conductivity meter, a flow meter, a solenoid-induced precipitation and a side-stream filtration.

Detail view of the heat transfer test section is shown in Fig. 2, which was made of two circular tubes. The two tubes formed a co-axial tube heat exchanger, where hot water moved in the inside of the inner tube and the cool water moved through the annulus gap made by the two tubes. The outside diameter of the core tube was 0.5”, whereas the inside diameter of the outer tube was 0.65”. The inner tube was a typical tube used in industrial chillers as seen in York, Carrier, and Trane chillers.

Typical inlet and outlet temperatures are sketched in Fig. 3. Other test conditions including heat flux, flow velocity and concentration are as follows:

Makeup: Philadelphia city water
No biocide addition
Flow rate (cooling water) = 1.5 gpm
Flow velocity (cooling water) = 1.1 m/s (Re = 5,300)

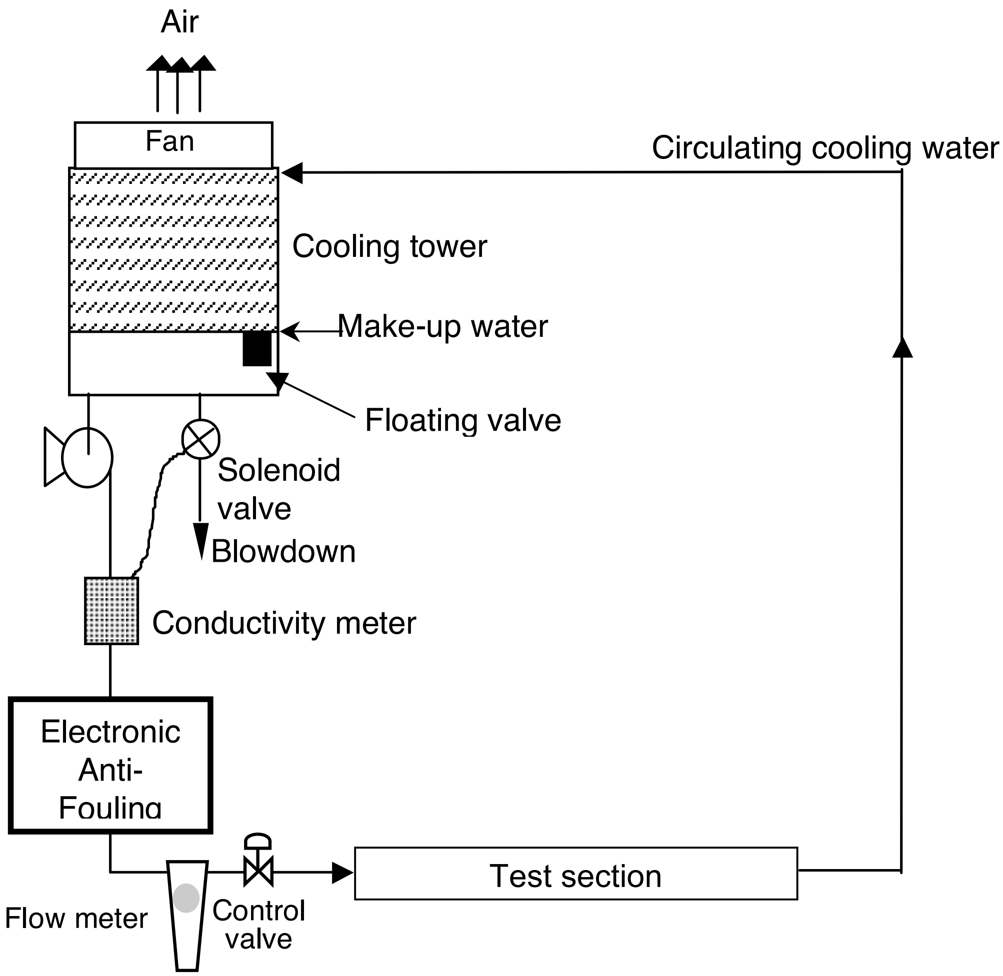

Fig. 1 Experimental system: A schematic diagram of the test facility for fouling resistance. 5 and 8 cycles of concentration.

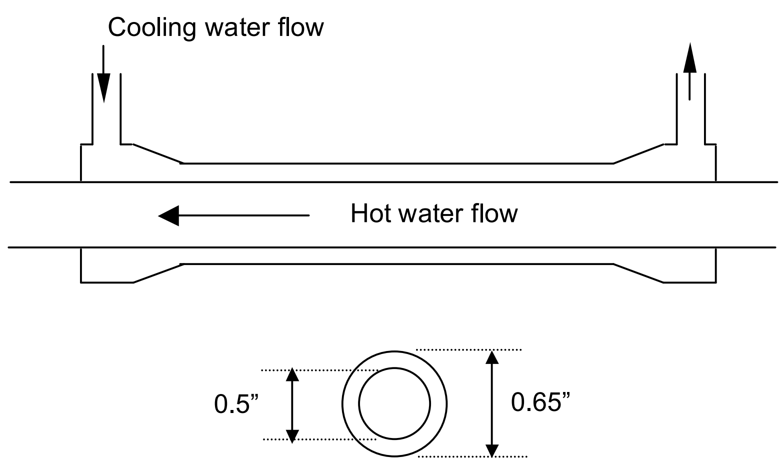

Fig. 2 Sketch of the main heat transfer test section. The main heat transfer test section consists of counter-flow concentric tube geometry.

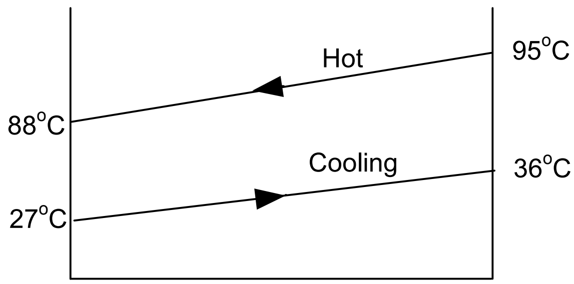

Fig. 3 Test Conditions including inlet and outlet temperatures, heat flux, flow velocity and concentration

<u>The second objective of the project was to demonstrate that IAF technology can limit scale deposits to maintain 90% heat transfer efficiency using cycle of concentration of 5.</u>

As mentioned in the original proposal, the fouling tests were conducted using a relatively high heat flux of 90-100 Kw/m^2 in order to accelerate fouling process, a practice which is common for fouling researches. Table 1 shows the test conditions of previous fouling studies, which also used similar levels of heat flux as in the present tests.

Table 2 shows test matrix and legends for the tests conducted in the project. WO means no treatment as baseline reference. W means tests with solenoid coil device but without filtration. R means a test repeated to confirm the accuracy of a previous test. F means a test with filtration.

Figure 4 shows a sketch of a filter unit used in the present study. The caking of $CaCO_3$ on the top of a sand filter medium took place. Thus, a form of back wash was necessary to keep the filter medium open for water flow.

Figure 5 shows test procedure showing how each test started and ended for 5 COC. The figure also shows the variations of the electric conductivity of circulating water in the simulated cooling tower, which was maintained within 5% of the set conductivity value. The blowdown was controlled by using a solenoid valve which was automatically controlled by the electric conductivity meter. The similar test procedure was used for 8 COC.

Figure 6 shows the results of fouling resistance over time for the cases with and without the EAF (electronic anti-fouling) treatment. Compared with the case of no-treatment, the case with the EAF treatment showed approximately 90% reduction in the fouling resistance. Figure 7 shows universal heat transfer coefficient over time

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for the cases with and without the EAF (electronic anti-fouling) treatment for the case of 5 cycles of concentration. The universal heat transfer coefficients [Ref. 1,2] for the case of no treatment were significantly below the 90% mark, whereas the case with a solenoid coil device without filtration showed the universal heat transfer coefficient above 90% mark. Figure 8 shows photographs of fouled heat transfer tubes taken at the end of fouling experiments. The heat transfer surface for the case without the EAF treatment was completely covered with scale, whereas the heat transfer surface for the case with the EAF treatment was barely covered with scale. Figure 9 and 10 show the fouling resistance curves and universal heat transfer coefficient curves for the case with the EAF treatment plus filtration (i.e., Integrated Anti-Fouling, IAF), which is marked as 5_W_F in the figures. The universal heat transfer coefficients for the case of IAF treatment (triangular symbols) were well above the 90% mark. Figure 11 shows photographs of fouled heat transfer tubes taken at the end of fouling experiments. The fouling resistance curve for the case of the IAF treatment remained almost below zero line, indicating that the IAF treatment kept the heat transfer surface completely scale free, and small scale particles made the heat transfer surface rough so that the heat transfer coefficient increased, thus bringing the fouling resistance into the negative regime.

Table 1 Data for heat flux used in laboratory fouling experiments , [Ref. 3-9]

References	Heat flux (kW/m^2)	Flow velocity (m/s)	Concentration (ppm)	Foulant
Hasson, 1968	1.6	0.25 - 0.82	110 - 575	Calcium
Kim & Webb, 1991	13	0.8 - 1.82	1500	Aluminum Oxide/ Ferric Oxide
Somerscales, 1991	28 - 52	0.9 - 1.0 1.4 - 1.5	2500	MgO
Nasrazadani, 1994	137	1 - 1.98	300 - 450	Calcium
Sheikholeslami & Watkinson, 1986	120 - 220	0.3 – 0.8	603 - 700	Calcium
Morse & Knudsen, 1997	276	1.0	490 - 650	TDS
Helalizadeh, 2000	100 - 400	0.5 - 2.0	1.0 - 2.5 / 0.25 - 1.0	Calcium Sulphate / Calcium Carbonate
Present study	90 - 110	1.1	1000 - 1600	Total hardness

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Table 2 Test matrix and legends for tests

A. 5 COC Test series: Conductivity set point = 3,000 □S

Run 5_WO	without EAF (electronic anti-fouling): baseline test
Run 5_WO_R	repeated test for without EAF (baseline test repeated)
Run 5_W	with EAF (without filtration)
Run 5_W_R	repeated test for with EAF (without filtration)
Run 5_WO_F	without EAF and with 10% filtration*
Run 5_W_F	with both EAF and 10% filtration* → **IAF Treatment**

* Filtration was done at a side-stream loop using a cartridge filter whose pore size was rated as 10 µm mesh. The flow rate through the side stream loop was 10% of the main loop flow rate.

B. 8 COC Test series: Conductivity set point = 5,000 µS /cm

Run 8_WO	without EAF: baseline test
Run 8_W	with EAF (without filtration)
Run 8_WO_F	without EAF and with 5% sand filtration**
Run 8_W_F	with EAF and 5% sand filtration → **IAF Treatment**

** Silica sand (see the diagram of sand filtration in Fig.4). The flow rate through the side stream loop was 5% of the main loop flow rate.

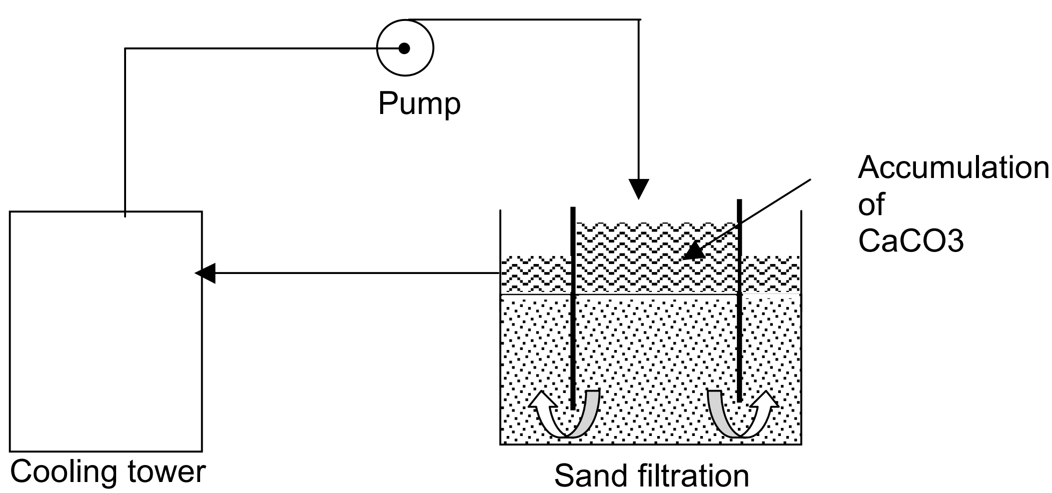

Figure 4 shows a sketch of a filter unit used in the present study.

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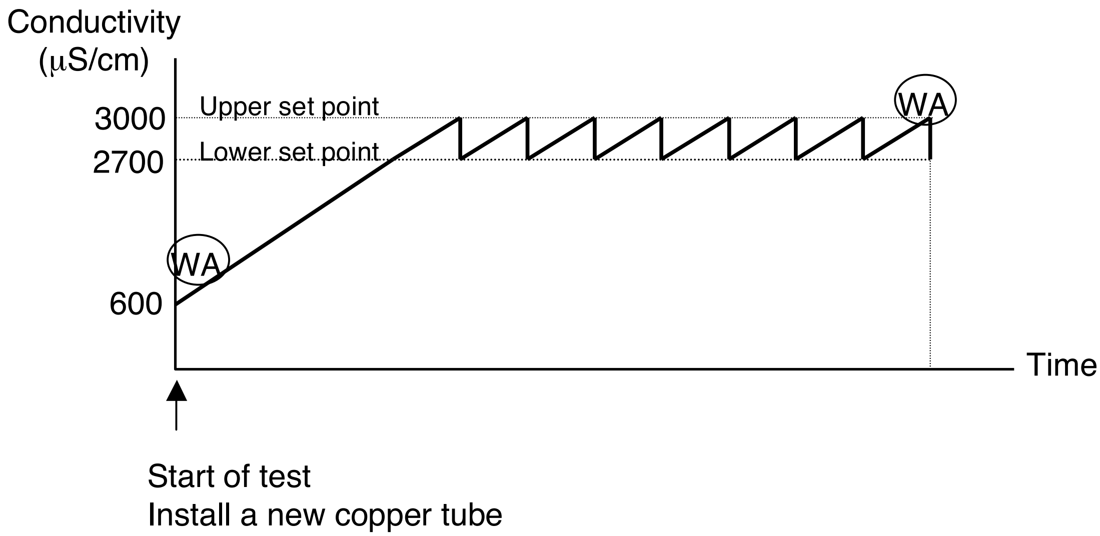


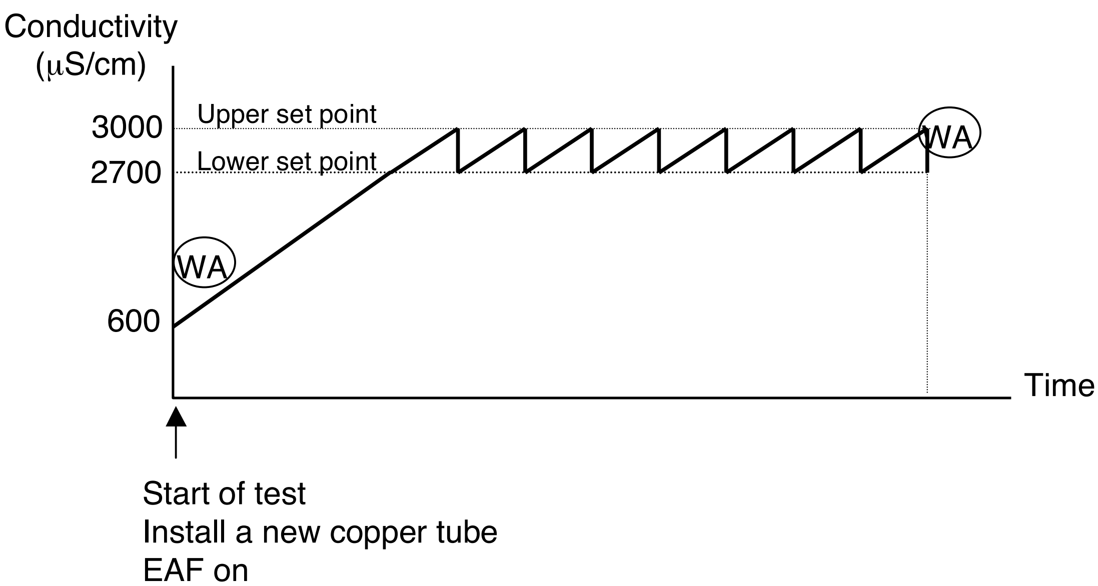


Fig. 5 Test Procedure showing the variations of the electric conductivity of circulating water in the simulated cooling tower for COC of 5.

Note) WA: timing of water analysis. Detail results of water analyses are given in Appendix II.

13

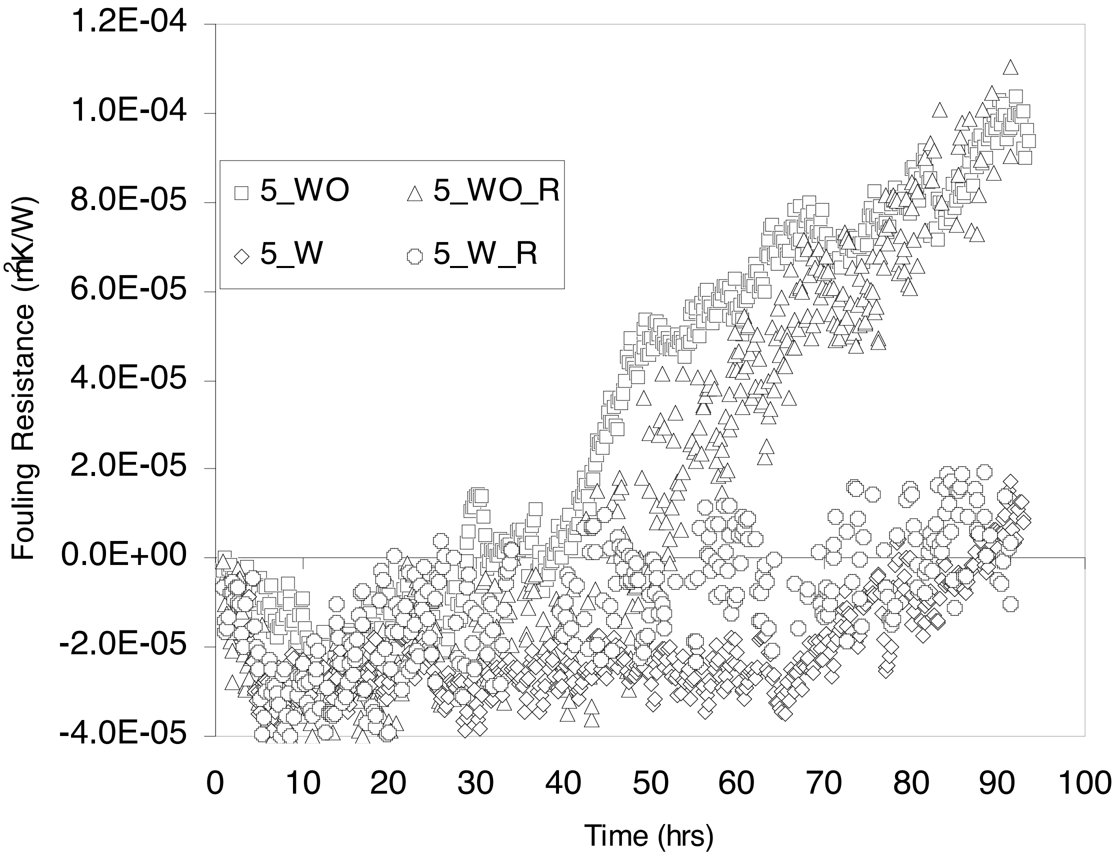


Fig. 6 Fouling resistances over time for the case of 5 cycle of concentration. The fouling resistances for the case of no treatment were significantly greater than those for the case with a solenoid coil device without filtration

Run 5_WO	without EAF (electronic anti-fouling): baseline test
Run 5_WO_R	repeated test for without EAF (baseline test repeated)
Run 5_W	with EAF (without filtration)
Run 5_W_R	repeated test for with EAF (without filtration)
Run 5_WO_F	without EAF and with 10% filtration*
Run 5_W_F	with both EAF and 10% filtration* → **IAF Treatment**

* Filtration was done at a side-stream loop using a cartridge filter whose pore size was rated as 10 μm mesh. The flow rate through the side stream loop was 10% of the main loop flow rate.

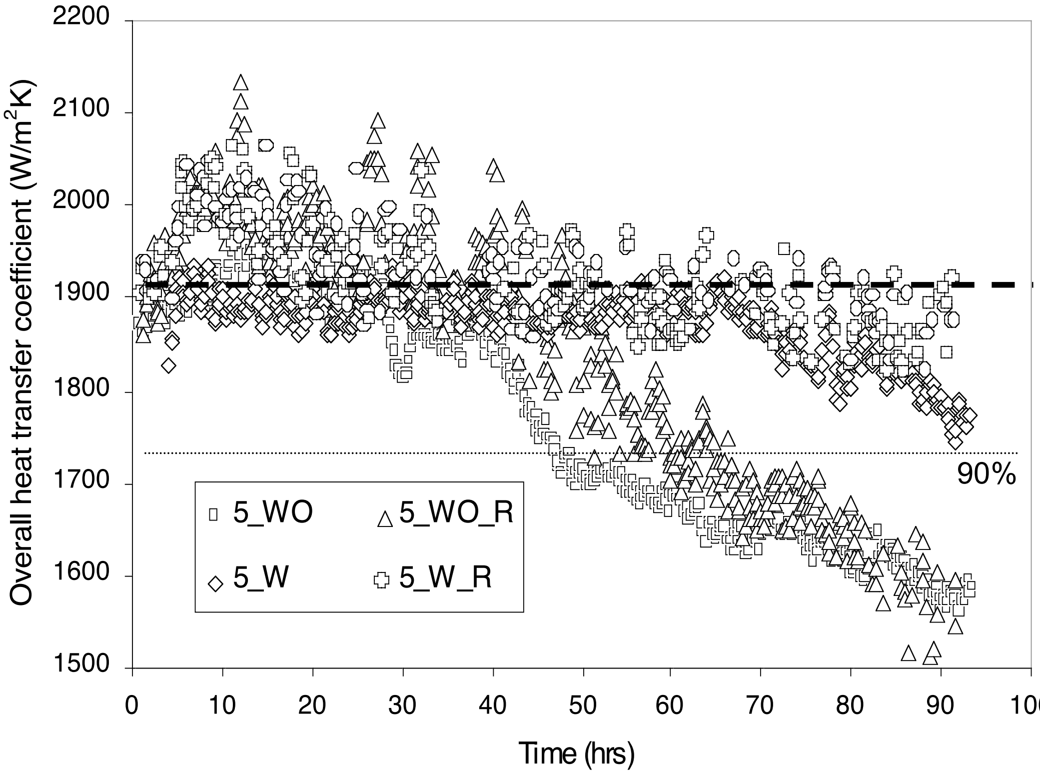
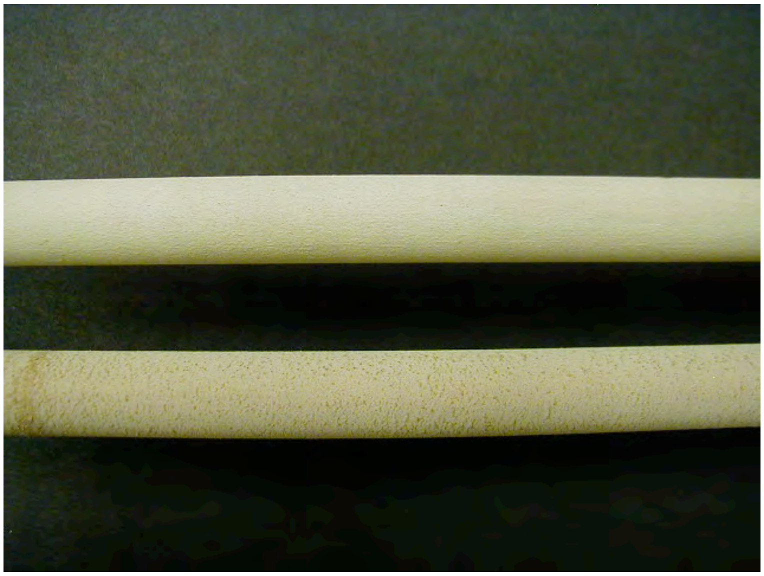


Fig. 7 Universal heat transfer coefficient over time for the case of 5 cycle of concentration. The universal heat transfer coefficients for the case of no treatment were significantly below the 90% mark, whereas the case with a solenoid coil device without filtration showed the universal heat transfer coefficient above 90% mark.

Run 5_WO	without EAF (electronic anti-fouling): baseline test
Run 5_WO_R	repeated test for without EAF (baseline test repeated)
Run 5_W	with EAF (without filtration)
Run 5_W_R	repeated test for with EAF (without filtration)
Run 5_WO_F	without EAF and with 10% filtration*
Run 5_W_F	with both EAF and 10% filtration* → **IAF Treatment**

* Filtration was done at a side-stream loop using a cartridge filter whose pore size was rated as 10 μm mesh. The flow rate through the side stream loop was 10% of the main loop flow rate.



5_WO

5_WO_R

5_W

5_W_R

Fig. 8 Fouled surfaces photographed after the completion of each test for the case of 5 cycle of concentration. The scale deposit for the case of no treatment was significantly greater than that for the case with a solenoid coil device without filtration.

Run 5_WO	without EAF (electronic anti-fouling): baseline test
Run 5_WO_R	repeated test for without EAF (baseline test repeated)
Run 5_W	with EAF (without filtration)
Run 5_W_R	repeated test for with EAF (without filtration)
Run 5_WO_F	without EAF and with 10% filtration*
Run 5_W_F	with both EAF and 10% filtration* → **IAF Treatment**

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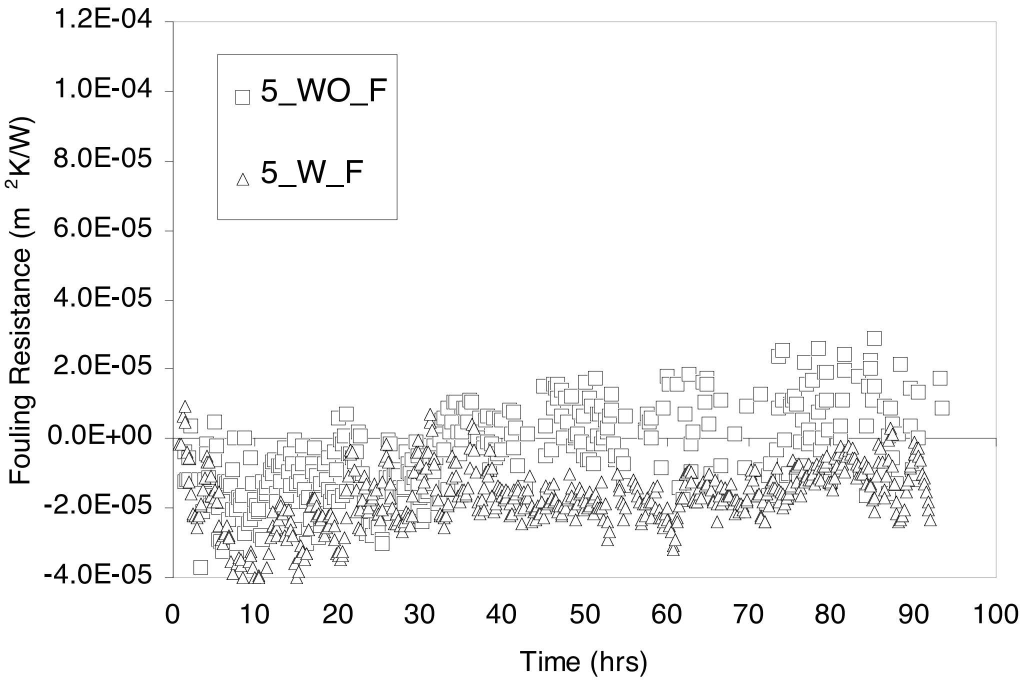

Fig. 9 Fouling resistances over time for the case of 5 cycle of concentration with filtration. The fouling resistances for the case with filtration were consistently less than those for the case without the filtration.

Run 5_WO	without EAF (electronic anti-fouling): baseline test
Run 5_WO_R	repeated test for without EAF (baseline test repeated)
Run 5_W	with EAF (without filtration)
Run 5_W_R	repeated test for with EAF (without filtration)
Run 5_WO_F	without EAF and with 10% filtration*
Run 5_W_F	with both EAF and 10% filtration* → **IAF Treatment**

* Filtration was done at a side-stream loop using a cartridge filter whose pore size was rated as 10 μm mesh. The flow rate through the side stream loop was 10% of the main loop flow rate.

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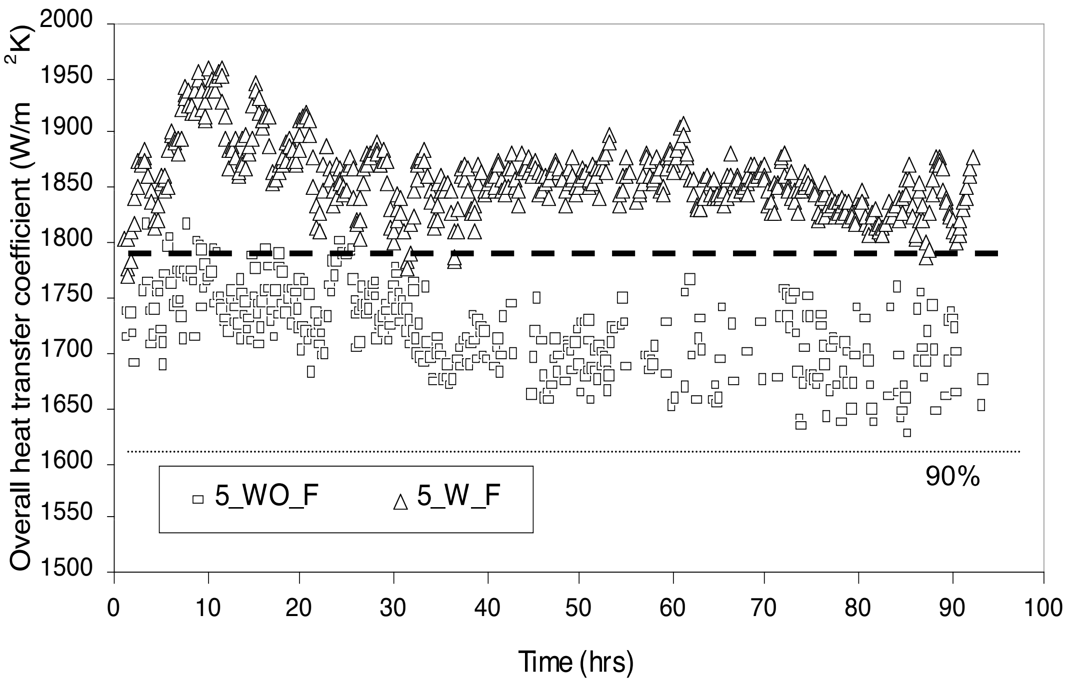

Fig. 10 Universal heat transfer coefficient over time for the case of 5 cycle of concentration. The universal heat transfer coefficients for the case of IAF treatment (triangular symbols) were well above the 90% mark.

Run 5_WO	without EAF (electronic anti-fouling): baseline test
Run 5_WO_R	repeated test for without EAF (baseline test repeated)
Run 5_W	with EAF (without filtration)
Run 5_W_R	repeated test for with EAF (without filtration)
Run 5_WO_F	without EAF and with 10% filtration*
Run 5_W_F	with both EAF and 10% filtration* → **IAF Treatment**

* Filtration was done at a side-stream loop using a cartridge filter whose pore size was rated as 10 μm mesh. The flow rate through the side stream loop was 10% of the main loop flow rate.

5_W_F

5_WO_F

Fig. 11 Fouled surfaces photographed after the completion of each test for the case of 5 cycle of concentration.

Run 5_WO	without EAF (electronic anti-fouling): baseline test
Run 5_WO_R	repeated test for without EAF (baseline test repeated)
Run 5_W	with EAF (without filtration)
Run 5_W_R	repeated test for with EAF (without filtration)
Run 5_WO_F	without EAF and with 10% filtration*
Run 5_W_F	with both EAF and 10% filtration* → **IAF Treatment**

* Filtration was done at a side-stream loop using a cartridge filter whose pore size was rated as 10 μm mesh. The flow rate through the side stream loop was 10% of the main loop flow rate.

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The third objective was to demonstrate that IAF technology can limit scale deposits to maintain 90% heat transfer efficiency using cycle of concentration of 8 using cycle of concentration of 8

Test procedure and data reduction methods were similar to those used for the case of COC of 8. Figure 12 shows variations of fouling resistances over time for the cases with and without the EAF treatment. At this high level of COC, the EAF treatment (without filtration) reduced the fouling resistance from 7.7×10^{-5} to 5.6×10^{-5} , i.e., by approximately 27%. Figure 13 shows universal heat transfer coefficients over time for the case of 8 cycle of concentration. The universal heat transfer coefficients for the case of no treatment (i.e., square symbols) were significantly below the 90% mark, whereas the case with a solenoid coil device without filtration showed the universal heat transfer coefficient at 90% mark, indicating the need of filtration. Photographs of fouled heat transfer surfaces are shown in Fig. 14, where the heat transfer surface obtained with no treatment was completely covered by scale, whereas the surface obtained with the case of the EAF treatment was partially covered by scale.

Figure 15 shows variations of fouling resistances over time for the cases with the EAF treatment plus filtration, see triangle symbols. The fouling resistance obtained with the EAF and filtration at the end of the test was approximately 1.3×10^{-5}, whereas that for the untreated case was 7.7×10^{-5}, indicating approximately 77% drop in the fouling resistance. Note that the filtration medium used in the test was sand, and the filtration percentage was 5% of the main flow rate. This type of the filtration practice is what is currently used in the field for large cooling tower and chiller applications. It is believed that by using a filtration system of smaller pore sizes and/or by increasing the percentage of filtration flow rate, one could further reduce the fouling resistance.

Figure 16 shows universal heat transfer coefficient over time for the case of 8 cycle of concentration. The universal heat transfer coefficients for the case of IAF treatment (triangular symbols) were well above the 90% mark. In fact, the IAF treatment maintained the universal heat transfer coefficients as the initial peak value.

Figure 17 shows the photographs of the fouled heat transfer surfaces taken at the end of the fouling tests. The surface treated by the EAF and filtration (i.e., IAF) appears to be very clean, scale free.

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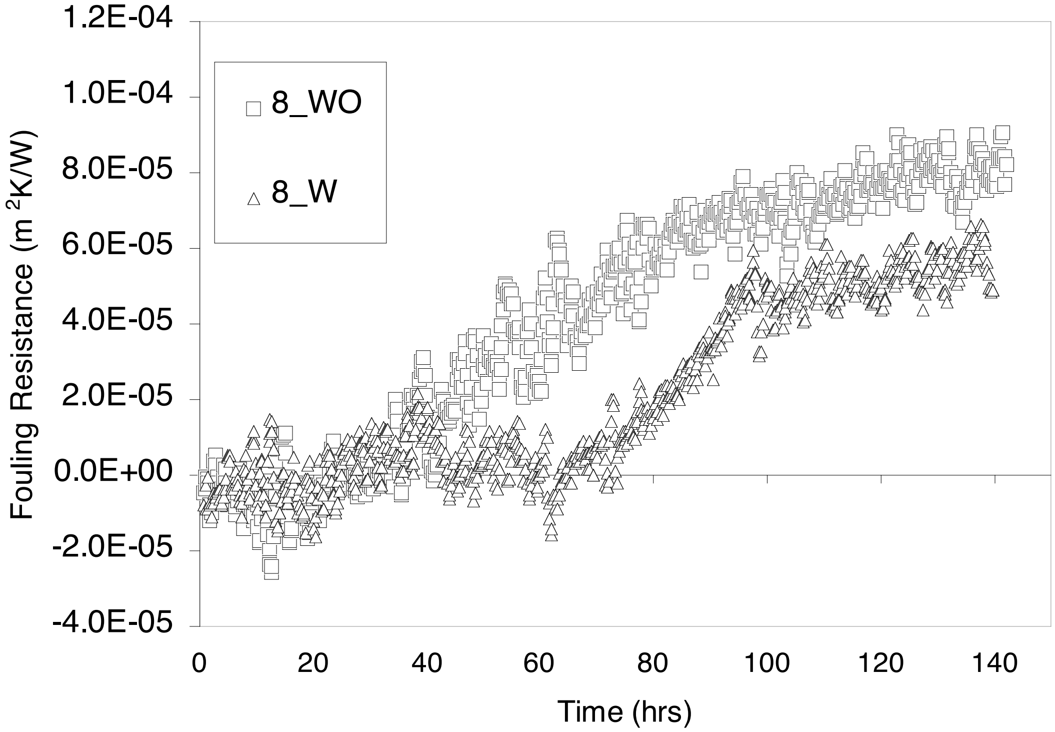

Fig. 12 Fouling resistances over time for the case of 8 cycle of concentration for no treatment case and the case with a solenoid coil device only. The fouling resistances for the case with the solenoid coil device were consistently less than those for the no treatment case.

Run 8_WO	without EAF: baseline test
Run 8_W	with EAF (without filtration)
Run 8_WO_F	without EAF and with 5% sand filtration**
Run 8_W_F	with EAF and 5% sand filtration → **IAF Treatment**

** Silica sand (see the diagram of sand filtration in Fig.4). The flow rate through the side stream loop was 5% of the main loop flow rate.

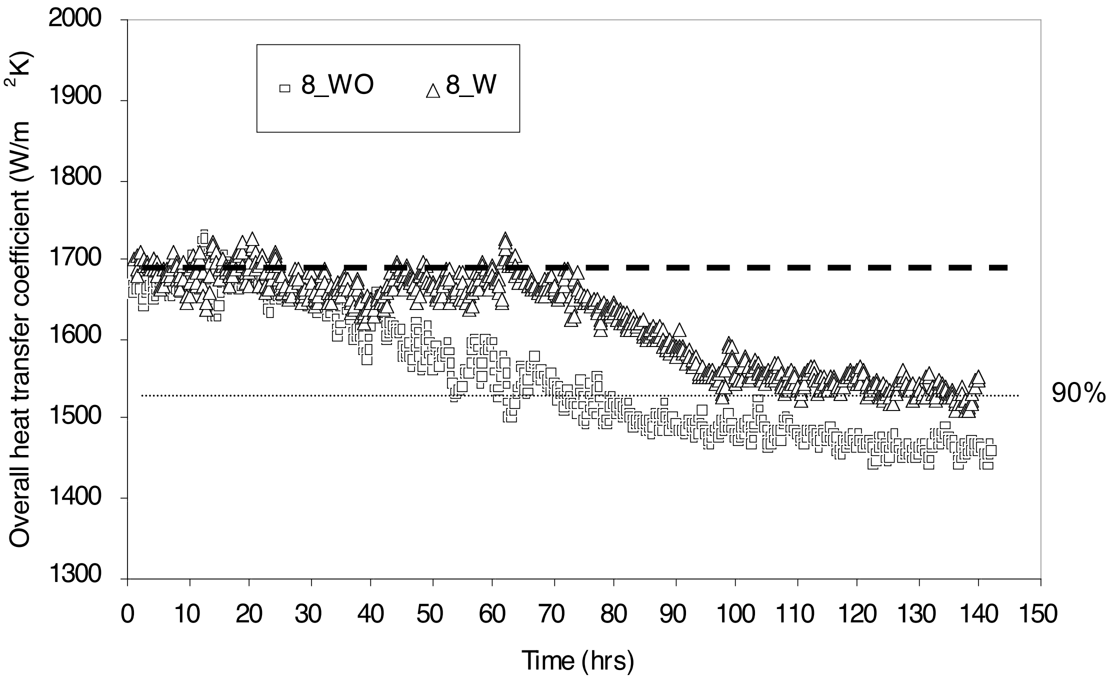

Fig. 13 Universal heat transfer coefficient over time for the case of 8 cycle of concentration. The universal heat transfer coefficients for the case of no treatment (i.e., square symbols) were significantly below the 90% mark, whereas the case with a solenoid coil device without filtration showed the universal heat transfer coefficient at 90% mark, indicating the need of filtration.

Run 8_WO	without EAF: baseline test
Run 8_W	with EAF (without filtration)
Run 8_WO_F	without EAF and with 5% sand filtration**
Run 8_W_F	with EAF and 5% sand filtration → **IAF Treatment**

** Silica sand (see the diagram of sand filtration in Fig.4). The flow rate through the side stream loop was 5% of the main loop flow rate.

8_WO

8_W

Fig. 14 Fouled surfaces photographed after the completion of each test for the case of 8 cycle of concentration.

Run 8_WO	without EAF: baseline test
Run 8_W	with EAF (without filtration)
Run 8_WO_F	without EAF and with 5% sand filtration**
Run 8_W_F	with EAF and 5% sand filtration → **IAF Treatment**

** Silica sand (see the diagram of sand filtration in Fig.4). The flow rate through the side stream loop was 5% of the main loop flow rate.

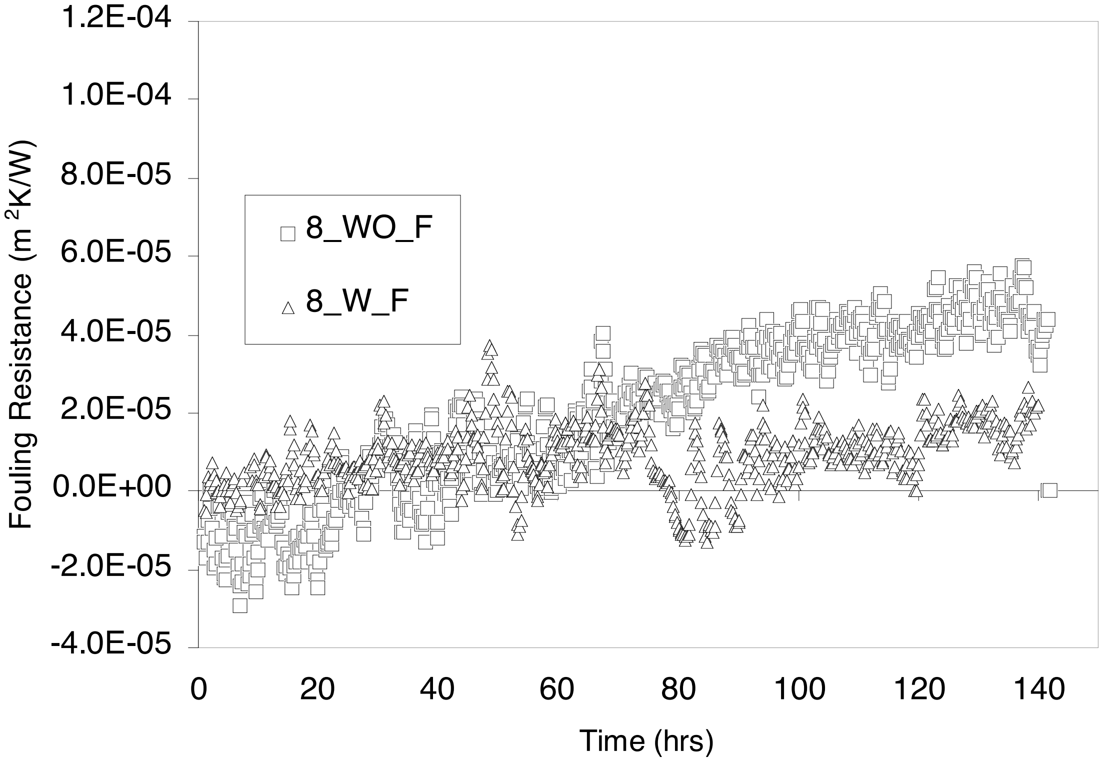

Fig. 15 Fouling resistances over time for the case of 8 cycle of concentration with and without filtration. The fouling resistances for the case with filtration were consistently less than those for the case without the filtration. The heat transfer surface with IAF case shows almost perfectly clean surface.

Run 8_WO	without EAF: baseline test
Run 8_W	with EAF (without filtration)
Run 8_WO_F	without EAF and with 5% sand filtration**
Run 8_W_F	with EAF and 5% sand filtration → **IAF Treatment**

** Silica sand (see the diagram of sand filtration in Fig.4). The flow rate through the side stream loop was 5% of the main loop flow rate.

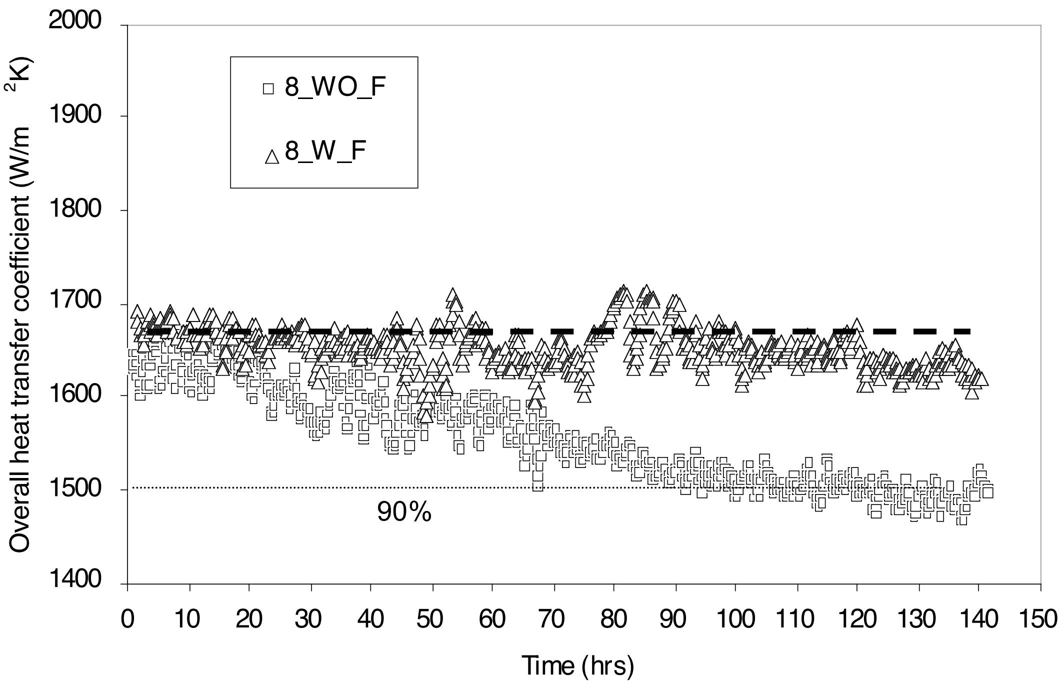

Fig. 16 Universal heat transfer coefficient over time for the case of 8 cycle of concentration. The universal heat transfer coefficients for the case of IAF treatment (triangular symbols) were well above the 90% mark. In fact, the IAF treatment maintained the universal heat transfer coefficients as the initial peak value.

Run 8_WO	without EAF: baseline test
Run 8_W	with EAF (without filtration)
Run 8_WO_F	without EAF and with 5% sand filtration**
Run 8_W_F	with EAF and 5% sand filtration → **IAF Treatment**

** Silica sand (see the diagram of sand filtration in Fig.4). The flow rate through the side stream loop was 5% of the main loop flow rate.

8_WO_F

8_W_F

Fig. 17 Fouled surfaces photographed after the completion of each test for the case of 8 cycle of concentration.

Run 8_WO	without EAF: baseline test
Run 8_W	with EAF (without filtration)
Run 8_WO_F	without EAF and with 5% sand filtration**
Run 8_W_F	with EAF and 5% sand filtration → **IAF Treatment**

** Silica sand (see the diagram of sand filtration in Fig.4). The flow rate through the side stream loop was 5% of the main loop flow rate.

<u>The fourth objective was to demonstrate that IAF technology can maintain a heat transfer coefficient of over 90% for the chiller tubes.</u>

As mentioned early, the present study produced fouling resistance data which indicated over 90% and 77% improvement for 5 and 8 cycles of concentrations, respectively, in the degradation of the heat transfer performance due to fouling. In terms of universal heat transfer coefficients, which indicate the performance of a heat exchanger, the project demonstrated that the IAF technology could maintain 90% of the initial peak universal heat transfer coefficients for cycles of concentration of both 5 and 8.

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Conclusions

The project has successfully developed and validated an Integrated Anti-Fouling (IAF) technology through experimental tests. The IAF technology consisted of electronic descaling system and filtration. The overall heat transfer coefficients in a heat transfer test section using a chiller tube were maintained 90% efficiency for both cycles of concentration of 5 and 8 compared with those of the clean scale-free state.

Based on the findings in the project, the chillers if equipped with the IAF technology can be operated within 10% of the maximum peak performance, resulting in significant energy savings. The present project clearly demonstrated that the combined use of the two, which is referred as the IAF technology, is a technology that is ready for commercialization.

Recommendations

One of the technical challenges involved in the commercialization of the IAF technology is in the use of filter. The project found that the calcium carbonate scale crystals were accumulated at the top of filter medium, caking into a hard concrete with time. This requires a design change in the filter so that the caking of calcium carbonate scale crystals can be avoided. Some of the back-washable filters are designed specifically to reduce the accumulation of calcium carbonate scale crystals so that the problem can be minimal, thus not causing the caking problem.

Public Benefits to California

The heat transfer performance of a water-cooled chiller degrades as the condenser tubes become fouled as water is used as a heat transfer medium. As the fouling decreases the efficiency of the chiller, the energy consumption increases. Typically, a large chiller runs at 0.6 kW/ton when its condenser tubes are clean, scale free. When the condenser tubes become fouled, the chiller runs at a level substantially greater than 0.8 kW/ton. The result in the project provides a solution to maintain the condenser tubes clean, scale free, thus maintaining the initial energy consumption for large chillers. The cost of the implementation of the technology is relatively small compared to the increased energy cost due to fouling in the condenser tubes at large chillers. If the results from the project is widely used in water-cooled chillers in California, water-cooled chillers can be operated it their initial peak efficiency.

Development Stage Assessment

J&D Thermo-Fluid Technology, Inc. (“J&D”) is a research and development company. This research project has proven the efficacy of the combined use of electronic descaling and filtration systems in the laboratory setting.

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Development Assessment Matrix

Stages / Activity	1 Idea Generation	2 Technical & Market Analysis	3 Research	4 Technology Develop-ment	5 Product Develop-ment	6 Demon-stration	7 Market Transfor-mation	8 Commer-cialization
Marketing								
Engineering / Technical								
Legal/ Contractual								
Risk Assess/ Quality Plans								
Strategic								
Production. Readiness/								
Public Benefits/ Cost								

Marketing

The integration of the electronic descaling system and filtration into a single package will be a marketing strength for this IAF technology. There are numerous manufacturers of filtration systems currently active in the marketplace, and there are also numerous manufacturers of electronic descaling systems active in the market. However only a very few development-stage companies have begun selling these technologies together as a package. And in these few cases, there is typically no scientific data to support these marketing efforts. The attempt to sell such technologies based on anecdotal evidence rather than rigorous scientific testing has created a vacuum of credibility in the marketplace for these solutions.

J&D is seeking to lead the effort toward better credibility and help break open this large market opportunity. J&D is exploring strategic relationships with manufacturers of filtration systems that will combine their market expertise and existing distribution capabilities with J&D's research and technology innovations.

Engineering/Technical

The IAF has passed the proof-of-concept stage through laboratory-based testing, and is now entering field-testing stage. J&D is exploring opportunities to install the IAF technology as an advanced solution in chillers located in local Philadelphia-area universities for the 2003 cooling season. Manufacturers of filtration systems and other peripheral components have agreed to support this field-testing stage by supplying products free of charge or at cost.

Legal / Contractual

J&D has entered in confidentiality agreements for research testing only. J&D has not formed any other binding legal or contractual agreements with potential strategic partners or made any commitments to distribution relationships with them.

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Risk Assessment / Quality Plans

Chiller applications face a broad range of biofouling issues ranging from algae to legionella that present significant risk to the marketplace and to local communities. For this reason, J&D is including peripheral components such as a brominador to control biological fouling in the upcoming field tests. Quality control issues with the backwashable filtration systems will be addressed by the filter manufacturer.

Strategic

J&D is following a strategy is based on key relationships with filter manufacturers and increasing credibility of its innovations through scientific testing.

Based on nearly a decade of contact with the chiller and water treatment industries, the principals of J&D have a good understanding of the strategic issues that this market segment is facing. In past years, the multibillion-dollar chemical water treatment industry has shown significant resistance to new mechanical and electronic water treatment technologies such as the IAF. The purchase of leading American chemical water treatment company Betz-Dearborn by General Electric Co. this year has marked an increasing sense of openness in the marketplace to cooperation between the two spheres.

The principals of J&D have contributed significantly to this increase in openness through the writing of numerous papers and presentations at industry conferences. J&D will continue to work toward increasing the credibility of innovative mechanical and electronic solutions through scientific testing and will market its innovations based on their clear benefits.

Production Readiness

Prototypes of the IAF technology are available for field testing. The technology is however not ready for mass production.

Public Benefits / Costs

J&D is focused on making its solutions economically viable for prospective customers. Relationships with organizations associated with state governments such as the CEC or NYSERDA, as well as federal agencies are likely to greatly assist in developing the credibility and stature of these efforts in the marketplace.

Endnotes
None

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Glossary

$CACO_3$: calcium carbonate
COC: cycle of concentration
EAF: electronic anti-fouling (i.e., without filtration)
IAF: integrated anti-fouling
SEM = scanning electron microscopy
WA: time of water sampling for water analysis
WO: no treatment
WOF: treatment with filtration only
WOR: no treatment repeated
W: treatment with solenoid coil device
W_R: treatment with solenoid coil device, repeated
W_F: treatment with solenoid coil device and filtration

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Appendix I

Figure 1 shows the general overview of a chiller and a cooling tower. The chiller consists of four major components: a compressor, a condenser, an expansion valve, and an evaporator. Since the condenser has to discard heat from the superheated refrigerant, it requires a heat sink, which is the cooling-tower water. As the cooling-tower water passes through the condenser tubes, the water is heated, and consequently, the dissolved mineral ions such as calcium and magnesium precipitate, coating the internally enhanced tube surface.

The condenser tubes used in a typical chiller are made of an internally enhanced tube. Since the cooling-tower water is circulated around the cooling tower three to four times, mineral concentrations in the cooling-tower water increases as water evaporates during each cycle. Typically, the concentration of the mineral ions in cooling-tower water is three to four times greater than that of the supply water (also called make-up water). Because of this high mineral concentration, scale deposits are common in chiller condenser tubes.

The concept of an IAF technology as applied to a chiller in a cooling-tower is shown in Figure 1. In Figure 1, the two components of the IAF technology have been added to the cooling-tower system: an electronic anti-fouling system and a side-stream filtration loop.

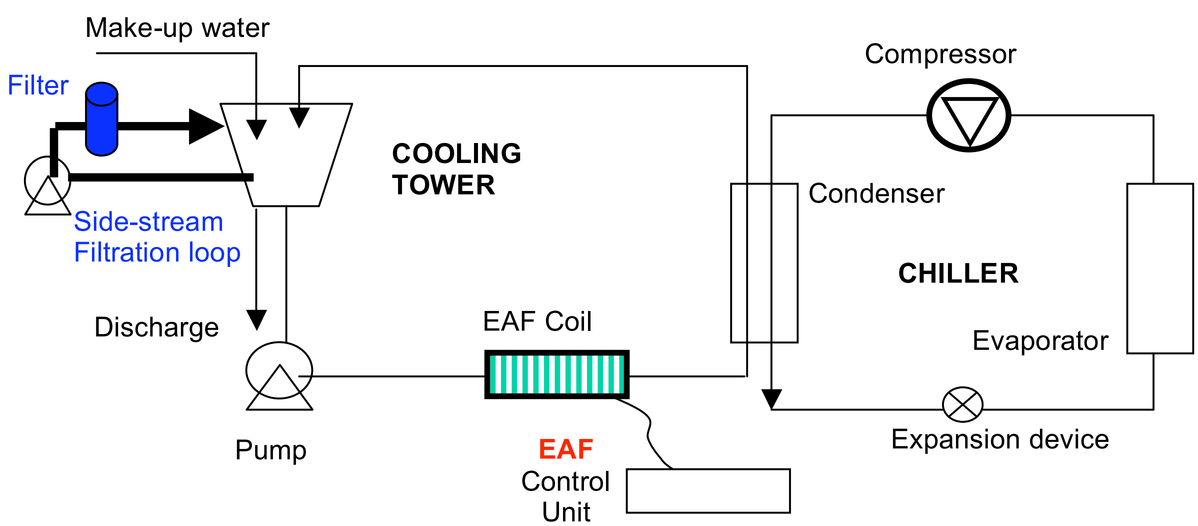

Fig. 1 The concept of an integrated anti-fouling technology using a solenoid-induced precipitation and a side-stream filtration

An SIP system consists of a coil and a control unit. The coil is wrapped around the condenser feed pipe to form a solenoid. The control unit produces a pulsing current to create an induced electric field inside the pipe, a phenomenon that can be described by Faraday's law [1]:

$$\int E \cdot ds = -\frac{\partial}{\partial t}\int B \cdot dA \qquad (1)$$

More descriptions of the use of solenoid-induced precipitation can be found elsewhere [2-6]. The induced electric field, which oscillates with time, provides molecular agitation to charged mineral ions such that the dissolved minerals collide and precipitate. As fluid temperature increases inside a heat exchanger, the nucleic particles grow to large crystals. Large crystal growth makes it possible to remove mineral particulates with the side-stream filtration system. As a result of the combination of SIP and filtration, fouling in the condenser tubes can be mitigated or prevented. Furthermore, as the mineral ions are removed through the side-stream filtration, the cycle of concentration in the cooling-tower water can be increased, thus resulting in water saving.

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Appendix II

Water analyses for 5 and 8 cycles of concentration cases

Water quality Data

	Run 5_WO			Run 5_W		
	makeup	circulating	Cycle	makeup	circulating	Cycle
Conductivity	585	3000	5.1	590	3000	5.1
Hardness	230	1060	4.6	240	1044	4.4
Calcium	180	820	4.6	182	716	3.9
Magnesium	50	240	4.8	58	328	5.7
Chloride	98	500	5.1	112	488	4.4
T.A.	90	380	4.2	96	380	4.0
pH	7.3	8.6		7.2	8.58	

	Run 5_WO_R			Run 5_W_R		
	makeup	circulating	Cycle	makeup	circulating	Cycle
Conductivity	612	3000	4.9	605	3000	5.0
Hardness	240	1000	4.2	198	1016	5.1
Calcium	172	716	4.2	142	780	5.5
Magnesium	68	284	4.2	56	236	4.2
Chloride	110	484	4.4	94	488	5.2
T.A.	96	344	3.6	78	344	4.4
pH	7.2	8.8		7.2	8.6	

	Run 5_WO_F			Run 5_W_F		
	makeup	circulating	Cycle	makeup	circulating	Cycle
Conductivity	569	3000	5.3	588	3000	5.1
Hardness	232	1024	4.4	240	1024	4.3
Calcium	176	668	3.8	170	720	4.2
Magnesium	56	356	6.4	70	304	4.3
Chloride	102	468	4.6	106	480	4.5
T.A.	94	344	3.7	90	320	3.6
pH	7.3	8.7		7.6	8.9	

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	Run 8_WO			Run 8_W		
	makeup	circulating	Cycle	makeup	circulating	Cycle
Conductivity	574	5000	8.7	590	5000	8.5
Hardness	152	1448	9.5	230	1480	6.4
Calcium	118	1088	9.2	145	1056	7.3
Magnesium	34	360	10.6	85	424	5.0
Chloride	95	1040	10.9	100	1060	10.6
T.A.	56	340	6.1	90	344	3.8
pH	7.4	8.4		7.2	8.42	

	Run 8_WO_F			Run 8_W_F		
	makeup	circulating	Cycle	makeup	circulating	Cycle
Conductivity	560	5000	8.9	605	5000	8.3
Hardness	166	1520	9.2	210	1640	7.8
Calcium	126	1100	8.7	130	1120	8.6
Magnesium	40	420	10.5	80	520	6.5
Chloride	92	1010	11.0	95	1005	10.6
T.A.	62	330	5.3	83	290	3.5
pH	7.4	8.5		7.3	8.6	

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Appendix III
Test Plan
An Integrated Anti-Fouling Technology for Energy Efficient Chillers
Young I. Cho, Ph.D.

1. **Objective:**

to demonstrate whether we can maintain the efficiency of a chiller at or near its manufacturer's design value during the entire cooling season.

2. **Measures of Success:**

(a) Can we demonstrate that IAF technology can limit scale deposits to maintain 90% heat transfer efficiency using cycle of concentration of 5?

(b) Can we demonstrate that IAF technology can limit scale deposits to maintain 90% heat transfer efficiency using cycle of concentration of 8?

(c) Can we demonstrate that IAF technology can maintain a heat transfer coefficient of over 90% for the chiller tubes?

3. **Data Required:**

(a) Reynolds number, which can be determined from density, flow velocity, pipe diameter, and fluid viscosity
(b) Fouling resistance, which can be determined from inlet and outlet temperatures of cooling and hot water in heat transfer test section
(c) Electric conductivity of circulating water
(d) Water chemistry data such as alkalinity, calcium and total hardness, pH, chloride,

4. **Data Acquisition Procedure:**

The flow rate of the cooling water will be set a predetermined value such as 5 gpm. The corresponding flow velocity in the cooling channel where fouling occurred will be calculated in terms of ft/s. The Reynolds number will be estimated based on the cooling water pipe
To calculate the fouling resistance, temperatures will be measured at four different positions: cooling-water inlet and outlet, and hot-water inlet and outlet. The cooling water enters the test section at approximately 25°C and will be heated to 28^{o}C, whereas the hot water enters the test section at approximately 95°C and will be cooled to 87^{o}C during the test.
After the cooling water passes the heat-transfer test section, it is sent to the cooling tower, where the water is cooled by evaporation. In order to maintain a constant volume of water in the system, the tap water supplied by the City of Philadelphia is added as make-up water, a procedure that is controlled by an automatic floating-valve system. As the number of cycles of concentration increases, the amount of mineral ions and other chemicals that are dissolved in water increases proportionally. The cycle of concentration (COC) is defined as the ratio of the concentration of dissolved ions in circulating cooling-tower water to that in the make-up water. At the completion of each test, the cycle of concentration is determined, which is estimated using the chloride concentration in water.

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Hot water is produced by an electric water heater and circulated at a flow rate of 2-5 gpm. The water heater has a heating element of 4.2 kW, and its temperature is controlled using a thermostat (Omega Engineering, Inc).
The cycle of concentration will be varied from 5 to 8. For COC of 5, the first test will be conducted without any treatment. The second test will be carried out by treating the cooling water with an integrated anti-fouling (IAF) method before the cooling water entered the test section. The IAF treatment uses a square-wave pulsing current at 500 Hz to create time-varying magnetic fields, which in turn produces an induced pulsating electric field in the circulating water according to Faraday's law. Excess mineral ions such as calcium and magnesium precipitate into mineral salts. The percentage ratio of the side-stream filtration flow rate to the main circulating flow rate will be either 5% or 10%. At the completion of 5-COC case, the COC of 8 will be conducted.
The fouling resistance is often calculated using the following equation:

$$R_f = \frac{1}{U_f} - \frac{1}{U_i} \quad (1)$$

where U_f is an overall heat transfer coefficient from a heat exchanger experiencing fouling, and U_i is the overall heat transfer coefficient from a clean heat exchanger. Both overall heat transfer coefficients are calculated from the following equation:

$$U = \frac{\dot{Q}}{A\Delta T_{lm}} \quad (2)$$

where ΔT_{lm} is a log-mean-temperature difference, which can be described as

$$\Delta T_{lm} = \frac{(T_{h,i} - T_{c,o}) - (T_{h,o} - T_{c,i})}{\ln\left[\frac{(T_{h,i} - T_{c,o})}{(T_{h,o} - T_{c,i})}\right]} \quad (3)$$

The heat transfer rate, $\dot{Q}$, will be estimated from both the heating and cooling channels as

$$\dot{Q} = [\dot{m}c_p(T_i - T_o)]_h = [\dot{m}c_p(T_o - T_i)]_c \quad (4)$$

Appendix IV :SEM Photographs (provided in a separate Microsoft file)

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